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**Title:** Trade-offs between economic and environmental performance of an autonomous hybrid energy system using micro hydro

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**Abstract**

This paper evaluates the trade-offs between economic and environmental performance of an autonomous energy system utilising an existing Micro hydro power plant while improving its future reliability. The analysis primarily focuses on developing sustainable alternative to excessive reliance on Diesel Gensets in fulfilling the increasing seasonal shortfall in electricity supply from standalone Micro hydros. First, a preliminary assessment is conducted using hypothetical future shortfall in electricity supply from a Micro hydro of 10%, 20% and 30%, compared to a baseline of 2% shortfall, which shows drastic increase in the environmental costs (combined human health and ecological) by as much as 400%, 900%, 1400% respectively from continued use of conventional Diesel Genset. In the next step, a 'Micro hydro sustainability indicator' is formulated as the ratio of environmental costs to net present costs of different hybrid options. This is estimated through a mixed assessment framework, which combines consumer engagement for understanding the current and the projected future diurnal and the seasonal electrical loads along with quantitative evaluation of the corresponding costs. Finally, a demonstration case study implements this framework at the Khun Pang micro hydropower project in Si Lanna National Park within Chiang Mai province, northern Thailand for two scenarios – Scenario 1 (circa 2016-17, annual shortfall of 4% i.e. 571 kWh); Scenario 2 (circa 2025, projected future annual shortfall of 12.5% i.e. 3904 kWh).

For smaller unmet load of up to 4% in Scenario 1, Diesel Genset turns out to be the most preferred hybrid option, irrespective of whether the environmental costs were included alongside the net present costs or not. However, for an increased future load of 12.5% in Scenario 2, including the environmental costs makes the hybrid Micro hydro-PV-Diesel-Battery system cost-competitive to the Diesel only option. Considering a 25-year project lifespan, it becomes the most sustainable solution for retrofitting micro hydro facilities in ecologically sensitive locations in order to meet future shortfall in electricity supply, with improved renewable penetration of up to 97.5%.

***Keywords**: Emission; Hybrid; HOMER; Micro hydro; Off-grid; Rural electrification*

## 1. Introduction

Owing to unprecedented levels of socio-economic and environmental costs associated with large scale hydro electricity generation projects, there is a growing interest in local mini/micro hydropower in several countries [1]. Micro hydro has been identified as one of the most affordable renewable energy solutions for rural electrification in a multitude of viable low-head sites in isolated areas throughout the world [2,3]. The global technical potential of small hydropower is estimated 150-200 $GW_e$; only about 20% of this potential has been exploited to date [4]. However, 100% reliance on such 'run-of-the-river' facilities may not be viable for off-grid applications owing to their seasonal dependence on the stream flow [5]. Specifically, tropical countries face issue of intermittent power supply from micro hydro during the dry season, which is expected to be further aggravated from dwindling stream flow owing to global climate change [6,7] and rapidly increasing rural/local electricity demands [8,9]. Conventionally, the seasonal shortfall in electricity generation from micro hydros have been fulfilled by Diesel generator backup [10]. With the Diesel fuel prices (DFP) projected to remain low for the next 10-15 years, according to the OPEC Forecasting of Crude Oil Price [11], this would inadvertently result in tendency of operating Diesel Gensets over longer operating hours to meet the increased electricity demand in the foreseeable future. However, the majority of such sites are located in ecologically sensitive areas in developing countries (e.g. highlands and national parks), and any further aggravation in the use of standalone Diesel Gensets as backup to fulfil such unmet loads would lead to potentially detrimental environmental impacts of pollutant emissions on the precious flora and fauna in the region and the local population. Thus, while on the one hand micro hydros have shown credible performance capability for offering local remedy to current local energy demands [12–16], their potential for meeting the growing rural electricity demand sustainably, mainly in the context of availability of cheaper Diesel over the short-to-near term future, is questionable since simple scaling up of the current practice is going to be unsustainable.

A large proportion of electricity must be produced by renewables by 2050 if full potential of renewables is to be exploited [17]. Autonomous hybrid renewable energy system (HRES), combining an existing micro hydro with supplementary renewable energy technologies, such as PV-Wind-Battery-Diesel generator, have received large interest for off-grid rural electrification owing to their reduced installation and operational and maintenance (O&M) costs [18]. For example, feasibility assessment of small hydro-PV-wind HRES in six remote areas in Ethiopia demonstrated the role of such HRES in offering cheaper electricity (costing less than $0.16/kWh), alleviating the excessive reliance of the rural population on fossil resources and biomass [19]. The majority of the literature on HRES using micro hydro highlights its technical feasibility and/or its long-term economic viability as the two most frequently adopted design metrics [7,13,19,20], as well, existing research has explored ideal conditions for micro-hydro development and how to maximise investment returns [21,22]. To date, consideration of its wider environmental sustainability, especially its fitness for purpose in ecologically sensitive areas, is less frequent and decision choices are primarily limited to optimisation of the renewable components for fuel prices and $CO_2$-qouta prices [23,24].

Incremental adoption of available distributed generation technologies is meant to decrease the environmental impact of energy sector, however, the planning and design of autonomous energy system using micro hydro is primarily concerned with techno-economic analysis and grossly overlooks the local and global environmental effects of the proposed solutions. Given, externalities minimisation is a fundamental goal to ensure real sustainability in energy systems [25,26], this paper addresses the crucial knowledge gap in developing autonomous renewable energy system, incorporating available micro hydro generation for ecologically sensitive locations by conducting comprehensive evaluation of the environmental costs (attributed to $CO_2$ and air pollution) alongside economic performance. The first part of the paper describes a mixed assessment framework for quantifying the tradeoffs between econmic and environmental performance of an autnomons hybrid energy system using Micro hydro, which extends the existing approach based on optimisiation of the net present cost. The framework is then implemented to a real case study site utilising an existing micro hydro power plant for off-grid electricity generation within a national park in northern Thailand for two scenarios – Scenario 1 (current, circa 2017), Scenario 2 (projected future, circa 2025) (described in details in **Section 3.6**). The generalised patterns have been analysed and discussed to strengthen the role of holistic evaluation in ensuring improved environmental performance of similar autonomous micro hydro based HRES globally.

## 2. Materials and methods

### *2.1 Framework for economic and environmental performance evaluation*

As a first step, a methodological framework is proposed going beyond the current practice implemented in techno-economic assessment models of minimising the Net present cost, NPC (i.e. capital, operation and maintenance and replacement costs) (**Figure 1a**). The proposed methodology extends this approach to techno-economic-environmental assessment by additional steps of consumer engagement and externalities minimization (i.e. social and ecological costs arising from $CO_2$ and air pollution emissions) alongside the NPC (**Figure 1b**; the additional steps shown in grey shading). Using this framework a range of technologies can be combined with an existing micro hydro to assess its feasbility in terms of a 'Microhydro sustainability indicator', which is formulated as the ratio of Environmental costs to Net present costs, ranging between 0 and 1 (lower score representing more environmentally benign hybrid Micro hydro system; >0.5 considered as the threshold for tipping the sustainability balance). This is meant to facilitate informed decision choices on suitable hybrid alternatives over its performance life-time taking into account their environmental costs, going beyond the short-term gains over the installation phase. Further, utilising a mixed-method, the proposed framework is meant to acquire real-world data on both the consumer electricity demands and their outlook to the solution developed, both during the deployment and the operation phases.

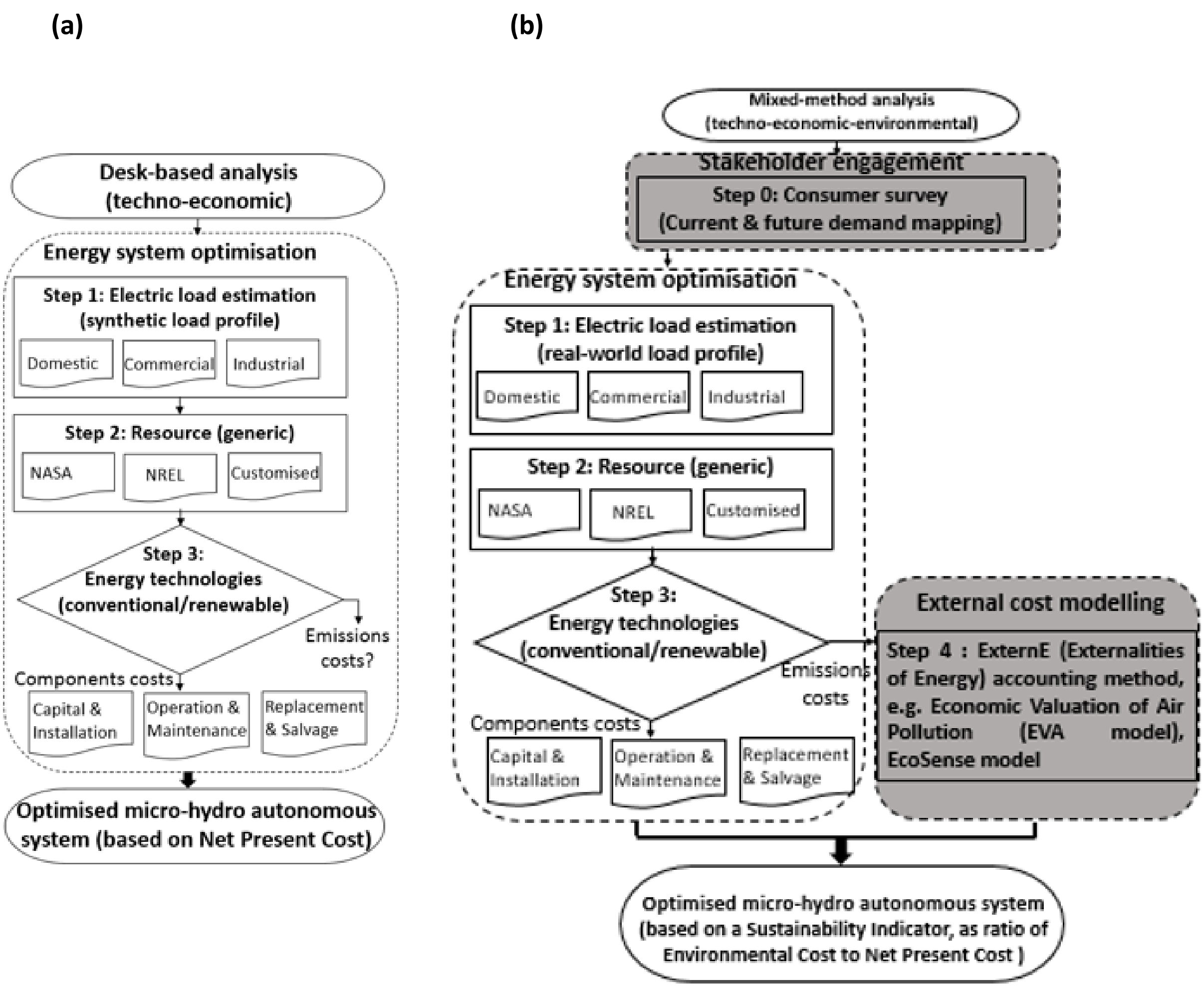


**Figure 1. Framework for assessing trade-off between economic and environmental performance of an autonomous energy system utilising a micro-hydro – (a) current practice; (b) proposed advancement to the current practice.**

*2.2 Hybrid energy system cost optimisation*

Decision to integrate different energy technologies into an existing Micro hydro takes an economic precedence, with important trade-offs between capital and operating costs. For example, renewable components typically have high capital but low operating costs, whereas Diesel Gensets have low capital but high operating costs. The Hybrid Optimization of Multiple Energy Resource (HOMER Pro®) software offers a standardised tool to conduct economic feasibility, stability and cost effectiveness of HRES through optimisation and sensitivity analysis of different renewable options and the corresponding cost estimates. A review of 68 computer-based tools for analysing the integration of renewable energy into various energy-systems has shown HOMER suitable for simulating stand-alone applications [27]. It is widely acknowledged as the professional HRES modelling tool by the US National Renewable Energy Laboratory and has been used in over 193 countries [14,19]. Key input parameters used in HOMER simulation include - electrical load demand, natural resource profiles (sun, wind, water, biomass, etc.), design specification (e.g. flow rate and head of micro hydro), costs of energy technologies (includes, capital, installation, operation and maintenance, replacement costs) and market parameters reflecting time value of money (discount rate, Diesel fuel price, inflation, etc.). The discount rate concept puts a value on time preference on money, which varies by location and time period considered; the choice of discount rate can largely affect the energy technologies which are relatively more competitive [28]. The private sector favours higher discount rates to maximise short-term profit, but these may be too high to capture the benefits of long-term social endeavours undertaken in the public sector, such as infrastructure and energy projects [28]. It is worth noting that, there is a distinction between real and nominal discount rate where inflation is included in the nominal rate [29].

The software models hourly annual (i.e. 8,760 hours) combinations of the available resources in order to meet the required system load and constraints. The model allows sensitivity analysis of different parameters (cost of energy, discount rate, amount of renewable energy component, a renewable fraction, electrical production of HRES, fuel consumption and emissions). The results of the simulation are shown using schematic of the system, along with graphs and tables showing the performance of each component and their corresponding costs. The outcomes are ranked as combinations of the hybrid components in terms of their NPCs in an ascending order [30].

*2.3 Environmental cost optimisation*

While the Micro hydro comes up as a clear winner in terms of the environmental costs from the operation and end of life phases, associating the external costs to the environment from operation of

Diesel back up can be complex, as there are several compounding environmental effects of different emissions to the local flora and fauna. A previous study conducted a conservative estimation of the environmental costs, comparing performance of a 100% renewable energy system with the business-as-usual scenario on the basis of six pollutant emissions ($SO_2$,$NO_x$, CO, particulates ($PM_{2.5}$), mercury, and lead), but it only considered damage to human health and the damage to nature and animal life was not addressed [31,32].

Our study assumes that currently at least 2% of the seasonal shortfall in electricity supply from an existing Micro hydro is fulfilled by Diesel Gensets globally. Using this as the baseline, a hypothetical assessment is conducted to assess the environmental costs for fulfilling future shortfalls in annual electricity supply of 10%, 20% and up to 30% from a micro hydro.

### 2.2.1 Air pollutant emissions

The pollutant emissions used in this study mainly accounts for fuel consumption and conversion technology of the Diesel generator in different hybrid energy system configurations modelled (**Section 3.6**), and includes the following six pollutants: Carbon Dioxide ($CO_2$), Carbon Monoxide (CO), Unburned Hydrocarbons (UHCs, mainly formaldehyde and alkenes as precursors of photochemical smog), Particulate Matter (PM), Sulphur Dioxide ($SO_2$), Nitrogen Oxides ($NO_x$). The total emissions have been estimated using the emissions factors (i.e. kg of pollutant emitted per unit of fuel consumed) for each pollutant, which were scaled up using the fuel consumption levels [30]. The emissions estimates include the following three assumptions: a) any carbon in the fuel that is not emitted as carbon monoxide or unburned hydrocarbons is emitted as carbon dioxide; b) the carbon fraction of the unburned hydrocarbon emissions is the same as that of the fuel; c) any sulfur in the burned fuel that is not emitted as particulate matter is emitted as sulfur dioxide.

### 2.2.2 External costs

The externalities of energy (ExternE) approach is applied to evaluate the environmental costs under two categories: a) human health; b) ecological [33]. The reported cost estimates from the integrated model system, EVA (External Valuation of Air pollution), developed by the Danish Centre for Energy, Environment and Health (CEEH) (http://www.ceeh.dk/) is used to derive the health-related economic externalities of the quantified air pollution emissions [32]. The ecological costs have been applied from the external costs, estimated using literature values on the environmental impact of the emissions expressed in terms of eutrophication, acidification and ecotoxicity potential [34,35]. The aggregated environmental damage costs for each emission category were then derived for the future years using baseline information for the reference year of the published material and associating a blanket annual increment rate to reflect the increasing marginal cost of emissions as per literature recommendation [36,37]

## 3. Demonstration case study

### *3.1. Site description*

The demonstration study is based on the Khun Pang village, which has a longstanding problem in meeting its electricity demand. The micro hydropower project is located in the remote rural and mountainous area in the Si Lanna National Park in the Chaing Mai province (19°11.0'N, 99°17.0'E) in northern Thailand (**Figure 2**). Northern Thailand has around 22 micro hydro power plants generating over 46.04 MW, which are managed by the Department of Alternative Energy Development and Efficiency [15]. However, these systems have highly seasonal characteristics, mainly owing to the reduced stream flow, which consequentially fail to support the demand for electricity in local villages [10]. This site was considered ideal for assessing the scoped tradeoffs given its proximity to a popular National Park, where environmental performance is paramount to protect the flora and fauna from detrimental effects of pollutant emissions during electricity generation. It is a stand-alone power generation unit, as it cannot be connected to the national grid owing to the mountainous terrain. It supports 48 households, a primary school and a temple. The existing set up comprises a 37 kW micro hydro turbine (cross flow type), a 35 kW synchronous generator, and the net head is 54.79 m. The headrace diameter and length are 400 mm and 800 m respectively. The penstock diameter and length are respectively 300 mm and 150 m. Weir height and length are respectively 1.5 m and 12 m [38].

The site has three seasons - summer, winter and monsoon [39]; the lowest water flow rate is during summer (< 50 $Ls^{-1}$). Consequently, the residents are not able to use electrical appliances during the peak summer period (typically between March and May) when the temperature is also high, mainly requiring electricity to pump water from bore wells in the storage tanks. The local school and the Buddhist temple also have higher electricity demands during summer, while the residents require electricity for irrigating their rice fields and for processing tea, chrysanthemums, grapes, strawberries, flowers [40].


**Figure 2. Map showing the clustering of micro hydro power projects (depicted as wheels) in Northern Thailand. Shown alongside in the inset is the location of the Khun Pang micro hydropower power facility and the weir near Si Lanna National Park, Chiang Mai province, Thailand [15].**

### *3.2. Current and future electrical loads*

A consumer survey was developed using the template from a previous successful survey (Appendix B) [41] and deployed at the study site to gather information on electricity consumption at two levels – one, household; two, community (school and temple). This formed the basis for estimating the typical load demand of the study site. In the first instance, semi-structured, face-to-face interviews were conducted following literature techniques to gather specific information [42]. Altogether 48 households (including a total of 110 adults, 20 school going children and 5 monks) were surveyed. The questionnaire asked a combination of closed- and open-ended questions [43]. The closed-ended questions used tick boxes and scale ranking, whereas the open-ended ones used question tags, such as “How much?” and “How many?” [42]. At the household level, typical questions queried on appliance type and size, mainly to gauge on the domestic electricity demand. Additional information was also acquired on community scale activities, such as water pumping for the school and temple, and the tea leaf cutting machine load. Further, the interview asked questions specific to understanding the future appliance needs of the residents in order to estimate the projected change in electricity demand over the next 10 years.

The appliance model and make data disclosed by the survey respondents was used to estimate the corresponding electricity load using appliance type and capacity (in Watts). Further, a diurnal consumption pattern profile for each appliance was generated, either on the basis of the respondents' stated preferences, or by applying some generic assumptions. All the collected data was analysed to estimate the primary and the deferrable loads for generating the modelling inputs, as described below.

### 3.2.1 Primary load analysis

Altogether, the response to the questionnaires on appliance usage from 36 households (i.e. 75% of the total households surveyed) and community scale activities (at the school and temple) was used to quantify the primary load. Response to each question on the type and the capacity of appliances used were combined with their daily usage to generate a database, which were then averaged to acquire a representative load for each appliance. The annual electricity consumption was adjusted for seasonal variations in temperature and humidity, given Chiang Mai has typically three distinct seasons – summer, monsoon and winter. The monthly consumptions were further allocated to weekdays and weekends on the basis of Thailand's annual calendar and list of national holidays in 2016. In order to quantify the daily load, the hourly appliance usage was classified into the following four typologies – continuous (e.g. refrigerator), used once (e.g. electric lighting), used twice (e.g. rice cooker used for 2 hours), season-dependent (e.g. cooler, heater). The estimated monthly weekdays and weekend loads for both the current and the future scenarios are respectively shown in Section 4.2.1.

### 3.2.2 Deferrable load analysis

The main deferrable load comprised of community appliance, such as the usage of the water pump for lifting of ground water to rooftop storage tanks at the school and temple and for the supply of water for irrigation. For this purpose the waterflow in the pipeline was estimated using pipeflow equations (Appendix A, Eqn. A.3). Two water pumps, with the nominal capacity of 1 kW each, were included for their usage three times a day (morning, afternoon and evening). The seasonal consumption was adjusted to reflect increased summer time water usage. The tea-leaf cutting machine, another important electrical appliance used by the community, was assumed to be used for two hours daily, cutting 200 kg $hr^{-1}$. For a nominal capacity of this appliance as 1 kW, the corresponding product specifications were obtained for a comparable product through market research [44].

### *3.3. Renewable resource analysis*

#### 3.3.1 Hydrology

Owing to absence of gauging stations at the selected site, direct flow rate measurements were not available. Instead, an empirical method was applied following the World Meteorological Organisation guideline for flow rate estimation at an ungauged site [45]. The monthly electricity production data for the Khun Pang Micro Hydropower Project was acquired from the Department of Alternative Energy, Thai Government, to estimate the waterflow (Appendix A, Eqn. A.2) [20]. For this purpose, the electricity output from the micro hydro was considered as a proxy for water flow rate in the Mae Pang stream, depending directly on the power of the turbine and the duration of generator operation. As shown in **Figure 3** (upper panel), the estimated flow rate is high during the monsoon period (June to November). The highest flow is in July. On contrary, the flow rate is quite low during the peak summer months (March to May).

#### 3.3.2 Solar radiation

The solar radiation data was collected from a site in terms of hourly data and MJ $m^{-2}$ unit. The annual average solar radiation in the case study area is approx. 19.2 MJ $m^{-2}day^{-1}$, whereas the corresponding values during the peak summer range between 20-24 MJ $m^{-2}day^{-1}$ [46]. This data was used to generate the monthly solar radiation profile by converting MJ $m^{-2}$ unit to kWh $m^{-2}$ unit for the purpose of HRES simulation in the next step (**Figure 3**, middle panel). The site receives the strongest solar radiation during the summer months, followed by relatively lower intensity during winter and the lowest during the monsoon period. The latter is mainly associated with cloud cover, which maps quite well with the clearness index (shown alongside on the secondary y-axis in **Figure 3**).

#### 3.3.3. Wind speed

Hourly wind speed profile (in m $s^{-1}$) for a site close to the case study were acquired, which were used to generate the monthly wind speed profile for the purpose of HRES simulations (**Figure 3**, lower panel). The wind speed at the site has the highest values during the monsoon season, followed by winter and the lowest during the summer season.

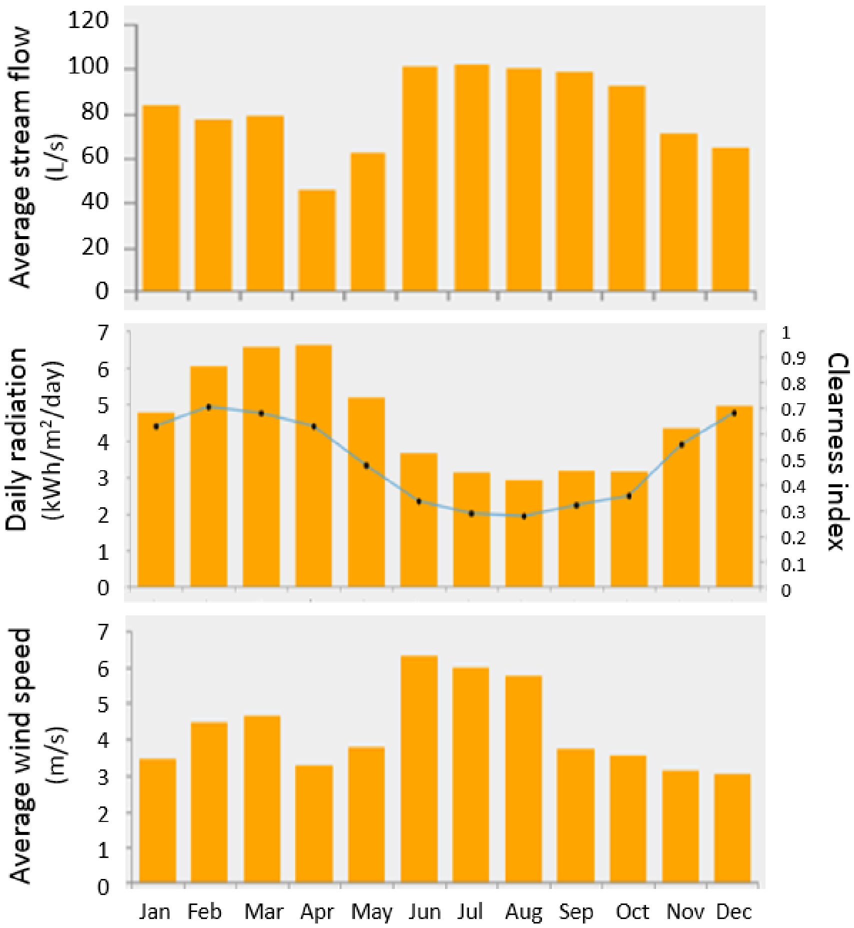


**Figure 3**. **Representative seasonal profile of environmental variables for the case study area – 1. Average stream flow rate (upper panel); Solar radiation (middle panel); Average wind speed (lower panel)**.

### *3.4 Cost analysis*

#### 3.4.1 Component costs

Specification and pricing for different renewable energy components were acquired from different component manufacturing companies and dealers in Thailand. Typically, prices from three manufacturers for each component specifications were acquired to obtain the average component prices. For example, all PV panels were costed using the prices acquired for multi-crystalline cell type from three manufacturers. **Table 1** provides the details of all the component specification and pricing used in the component analysis.

**Table 1. Specifications and prices of the hybrid energy components used.**

| RE Component | Type/Model | Capacity | Capital ($) | Replacement cost ($) | O&M cost ($/years) | Life time (years) | Efficiency (%) |
|---|---|---|---|---|---|---|---|
| Solar PV | Generic Flat Plate PV | 1 kW | 781.00 | 781.00 | 2.58 | 20 years | 15.98 |
| Wind Turbine | Generic | 1 kW | 4,038.00 | 4,038.00 | 40.38 | 20 years | - |
| Hydro Turbine | Natel FreeJet | 32 kW | - | - | - | 30 years | 60.00 |
| Diesel Generator | Autosize Genset | 1 kW | 588.00 | 588.00 | 0.040 $/hours | 15,000 hours | - |
| Battery | Generic 1 kWh Li-Ion (ASM) | 1 kWh | 641.00 | 641.00 | 10.65 | 5 years | - |
| Converter | System Converter | 1 kW | 686.00 | 686.00 | - | 15 years | 90.00 |

3.4.2 Diesel fuel prices

In order to establish the economic performance of the hybrid energy system, the sensitivity of the energy production was considered in terms of Diesel fuel prices (DFP). This is assessed in the context of the anticipated fluctuations in crude oil price forecasted by the Organization of the Petroleum Exporting Countries (OPEC) over the next 20 years [11]. As a first step, the average crude oil prices from OPEC and Thailand in 2016 were compared [47,48]. Thereafter, the crude oil price forecasts for Thailand were calculated and converted into Diesel prices forecasts from 2016 to 2040 by using the Thai Baht exchange rate in US dollars. As described in the following sections, the DFP step values of 0.75, 1.0, 1.25 and 1.50 $\$L^{-1}$ have been used, first to assess the sensitivity of the hybrid energy system modelling, and then for the scenarios modelling of cost-effective HRES for the site (see Section 3.6).

### *3.5 Sensitivity analysis*

A sensitivity analysis from HOMER simulation was used to confirm the best case for the two HRES scenarios following literature methods [49,50]. For each of the sensitivity values HOMER simulates all the system in their respective search space. The model sensitivity was assessed for the following sets of parameters: DFP (0.75, 1.0, 1.25, 1.5 $\$L^{-1}$); solar radiation (3, 4, 5, 6, 7 kWh $m^{-2}$ $day^{-1}$); wind speed (3, 4, 5, 6, 7 $ms^{-1}$). Given all the modelled scenarios used the existing micro hydro with fixed production capacity, it was excluded from the sensitivity analysis.

### *3.6 Scenario analysis*

Two scenarios have been considered – **Scenario 1**: complements the existing micro hydro to meet the current load demand (circa 2016-17, annual shortfall of 4% i.e. 571 kWh); **Scenario 2**: simulates a plausible HRES design utilising the existing micro hydro to meet the 24-hour future electricity load demand (circa 2025, projected future annual shortfall of 12.5% i.e. 3904 kWh). The latter incorporates the enhanced electrical load from increased appliance usage by the local residents at different time of the day, derived from the survey (**Section 3.2**). For each scenario, the following three cases with increasing complexity are evaluated: *Case I* – Economically preferred, i.e. cheapest initial cost (Micro hydro with Diesel back up); *Case II* – Intermediate, i.e. low initial cost (Micro hydro-Diesel backup-Battery storage); *Case III* – Environmentally preferred i.e. reduced Diesel Genset usage (includes Microhydro-PV- Diesel backup-Battery storage). The details of the hybrid system configuration (number and/or sizing of the components) for the individual cases for the two scenarios are shown in **Table 2a**. For scenario 2, the maximum forecasted DFP is 1.5 $\$ L^{-1}$. However, the forecast for crude oil prices rise in Thailand is expected to trail further owing to slow economic growth and steady rise in usage of alternative energy (Petroleum Institute of Thailand, 2016). On this basis a slightly lower DFP of 1.25 $\$ L^{-1}$ is used for Scenario 2. Further, an electricity tariff of 0.14 $/kWh is applied to calculate the revenue generation (@3.9 baht/kWh, circa 2017 average electricity price in Thailand). The annual inflation rate for all the scenarios were kept at 2%. These were combined with the cost information from **Table 1** to acquire the corresponding Net present costs for the different hybrid configurations in HOMER Pro®. The environmental costs applied to the two scenarios are shown in **Table 2b**.

It is noteworthy that while the two scenarios were given distinct load profiles, the economic and environmental costs of all these combinations were evaluated using identical resource profiles acquired directly from the Thai government records for 2016 (**Figure 3**), assuming the timestep considerably short for introducing any meaningful alteration in resource profiles for hydro, solar and wind data during the summer, winter and rainy seasons.

All the hybrid options introduced to the micro hydro were assumed to have a 25-year project lifespan, and only options returning zero unmet load value were considered in order to demonstrate the reliability of the system over different seasons. The system architecture for HOMER simulation applied to scenarios 1 and 2, with representation of the renewable energy components, and an electrical load in AC and DC electrical bus bar, are shown in **Figure 4**. The configuration for Scenario 2 includes an additional deferrable load.

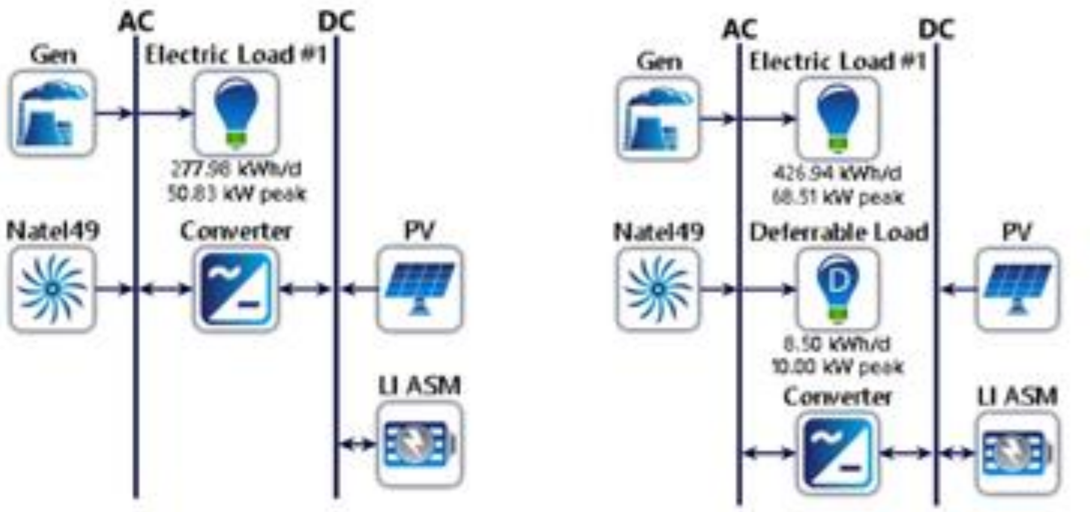


**Figure 4. Schematic of HOMER simulation hybrid system architecture for Scenario 1 (left panel); Scenario 2 (right panel).**

**Table 2a. Hybrid system configuration (number and/or sizing of the components) parameters simulating the individual cases for the two scenarios**

| Hybrid Energy System Scenario | Renewable fraction (%) | Diesel Genset (kW) | DFP ($\$ L^{-1}$) | Discount rate (%) | Battery (# units @1kWh capacity) | PV (# units @1kW capacity) | Converter (# units @1kW capacity) |
|---|---|---|---|---|---|---|---|
| **Scenario 1** | | | | | | | |
| *Case I* | 96 | 56 | 0.75 | 6 | 0 | 0 | 0 |
| *Case II* | 96 | 56 | 0.75 | 6 | 27 | 0 | 17 |
| *Case III* | 98 | 56 | 0.75 | 6 | 37 | 1 | 22 |
| **Scenario 2** | | | | | | | |
| *Case I* | 87.5 | 77 | 1.25 | 8 | 0 | 0 | 0 |
| *Case II* | 90 | 77 | 1.25 | 8 | 50 | 0 | 18 |
| *Case III* | 97 | 77 | 1.25 | 8 | 71 | 21 | 33 |

**Table 2b. Environmental costs applied to the two scenarios**

| Air pollutant | Scenario 1 | Scenario 2 |
|---|---|---|
| $CO_2$ | 0.050624 | 0.053664 |
| CO | 0.003955 | 0.006995 |
| HC (as VOC) | 0.1582 | 0.16124 |
| PM ($PM_{2.5}$) | 1344.7 | 1344.703 |
| $SO_2$ | 23.73 | 23.73304 |
| $NO_x$ | 18.193 | 18.19604 |

## 4. Results and Discussion

### *4.1 Trade-off between economic and environmental performance*

Considering a project lifespan of 25 years, a hypothetical assessment is conducted assuming continued use of conventional Diesel Genset in foreseeable future to fulfil the incremental shortfall in electricity supply from a Micro hydro of 10%, 20% and 30%. The output parameters include total number of hours of operating the diselse Genset over this period, Net present cost (includes capital costs, O&M and costs for replacing the Diesel Genset after nominal operating life of 15000 hours, see Table 1), and the associated environmental costs (combining climate and air quality costs), which are compared to a baseline of 2% shortfall (27 kWh). Results suggest the Diesel Genset usage time, the corresponding O&M costs and the associated environmental costs drastically increase by as much as 400%, 900%, 1400% respectively compared to the basline, whereas the increase in the net present cost is 262%, 539% and 901% (**Table 3**). The Micro hydro sustainability indicator clearly performs poorly (overshooting 0.5 threshold) for all electricity shortfall over 10%, when fulfilled solely by Diesel Genset. However, as shown later in the case study results (Section 4.2.3), the choice of alternative hybrid combination allows to bring down the indicator score to as low as 0.08 for a shortfall in electricity supply of 12.5% met by a Hydro-PV- Battery-Diesel system. This clearly shows the merit of the proposed framework in accounting for the environmental costs while ensuring long-term sustainability of a hybrid micro hydro system.

**Table 3. Indicative estimates of the variation in the economic and environmental performances of a hybrid system with Diesel Genset only in supporting a shortfall in electricity provision from an existing Micro hydro (shown alongside are the corresponding % change to the baseline scenario)**

| Annual supply shortfall from Micro hydro | Diesel Genset usage (hrs) # | Total O&M costs ($)# | Net present cost, NPC ($)# | Environmental cost, ENV ($)# | Total costs (NPC + ENV) # | Microhydro Sustainability Indicator (ENV/NPC) |
|---|---|---|---|---|---|---|
| **2% (Baseline*)** | 4375 | 20690 | 53618 | 19191 | 72809 | 0.36 |
| **10%** | 21,875 *(400%)* | 103,448 *(400%)* | 194,000 *(262%)* | 95,957 *(400%)* | 289,957 *(298%)* | 0.49 |
| **20%** | 43,750 *(900%)* | 206,896 *(900%)* | 342,724 *(539%)* | 191,914 *(900%)* | 534,638 *(634%)* | 0.56 |
| **30%** | 65,625 *(1400%)* | 310,344 *(1400%)* | 536,724 *(901%)* | 287,871 *(1400%)* | 824,595 *(1033%)* | 0.54 |

* represent shortfall of 2% in Micro hydro electricity generation fulfilled by Diesel Genset only.

# over 25 year project lifespan

*4.2 Case study results*

4.2.1 Electrical load estimation

Estimates of electricity demand have been made respectively using the current electricity usage data (Scenario 1) and the expected future load for Khun Pang Village from the questionnaire survey (Scenario 2). **Figure 5** compares the monthly electrical demand for Scenarios 1 and 2. Overall, the load demand is high in summer for both the scenarios, which is generally expected in Thailand. On contrary, while the current (Scenario 1) load demand for winter months remains relatively low owing to under utilisation of electrical appliances, this is expected to rise in scenario 2 because of increased use of water heaters in Chiang Mai, as it is located in the colder region of northern Thailand. The corresponding monthly maximum consumption loads are found for May for both scenarios 1 and 2 (respectively 8,800 kWh and 13,759 kWh) and the corresponding monthly minimum consumption loads are in February for both the scenarios 1 and 2 (7,858 kWh and 12,256 kWh). The annual average daily load (AADL) for Scenario 1 is estimated as 277.98 kWh $day^{-1}$ and the Load Factor (LF) is 0.23. Shown alongside on the right are the corresponding daily electrical load profiles, showing high morning, evening and bed time peaks. Moreover, the electrical peak load is in the evening, because this is when electrical users light bulbs and turn on many appliances such as rice cooker, TV and electric fans. The average daily load is found to be 11.58 kW. Further, the peak load and the minimum loads were respectively estimated as 50.83 kW and 17 kW.

The annual average daily load (AADL) for Scenario 2 is estimated as 426.94 kWh $day^{-1}$ and the Load Factor (LF) is 0.26. While the electric load pattern remains similar to Scenario 1 (i.e. high in the morning, evening and before bed time) (**Figure 5**, top right panel), there is a noticeable shift in the electrical peak load to the morning. This is attributed to usage of many additional appliances in the morning, such as rice cookers, TVs, electric fans, electric kettles, water heaters and light bulbs, mainly driven by seasonal growth in demands during the winter and the monsoon seasons. The corresponding peak load and the minimum loads were respectively estimated as 68.51 kW and 22 kW.

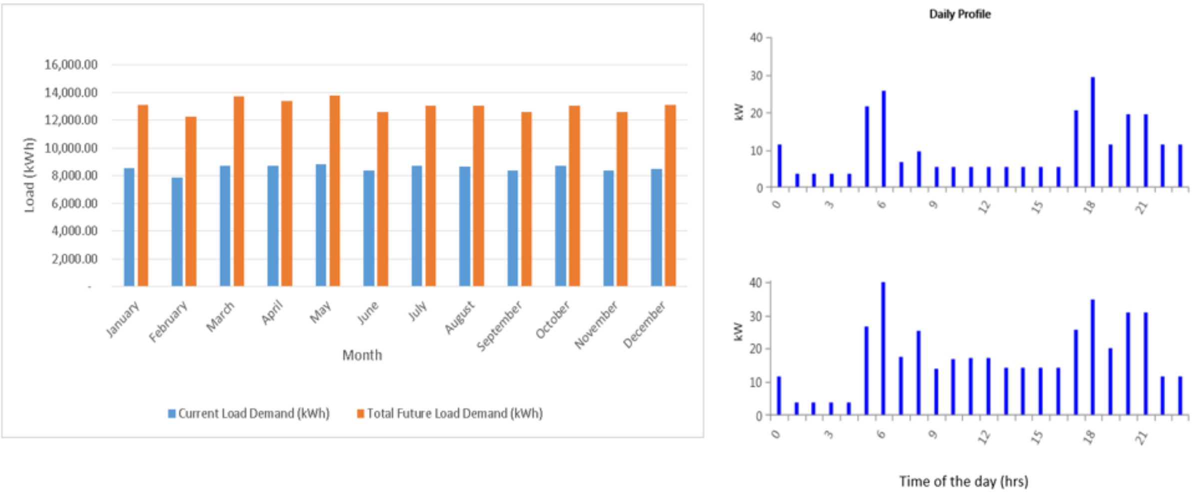


**Figure 5**. **Estimated monthly electricity demand in Khun Pang Village for Scenario 1 (current) and Scenario 2 (future). Corresponding annual average daily electrical load profiles shown alongside on the right.**

For the deferrable load, the AADL was 8.5 kWh day$^{-1}$ and the peak load was 10 kW. Storage capacity is 20 kWh. Overall, on monthly basis, the highest load is found over summer around 10.0 kWh day$^{-1}$, and during winter and monsoon around 8.0 kWh day$^{-1}$.

4.2.2 Model sensitivity analysis

For scenario 1, with the lower DFP of 0.75 \$ L$^{-1}$, the Hydro-Diesel-Battery HRES was the most cost-effective option for the majority of solar radiation range, as long as the DFP remained less than 1.4 \$ L$^{-1}$ . However, when DFP exceeded 1.4 \$ L$^{-1}$, the Hydro-PV-Diesel-Battery presented itself as a suitable option for the solar radiation range between 3.5 to 4.2 kWh m$^{-2}$ day$^{-1}$. Overall, for scenario 2, the Hydro-PV-Diesel-Battery HRES was considered as the optimal system across the full range of solar radiation and DFPs analysed.

**Table 4a** shows the overall outcome of the HRES simulation within the DFP range of 0.75 to 1.5 \$ L$^{-1}$ for Scenario 1 in the ascending order of costs (i.e. the topmost as the most economical). This table shows the ranking of cost effectiveness from the cost of energy (COE) and net present cost (NPC). The Hydro-Diesel-Battery system remains cost effective between the DFP range of 0.75 and 1.25 \$ L$^{-1}$ (COE: \$0.0705, NPC: \$92,441), while the hybrid Hydro-PV-Diesel-Battery system appears to be the most cost effective for the DFP range 1.5 \$ L$^{-1}$.

**Table 4a. Output of Scenario 1 sensitivity analysis for Diesel Fuel Price range 0.75 to 1.5 $ L$^{-1}$.**

| Sensitivity | Architecture | | | | | | | Cost | | System | | | | Gen | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Diesel Fuel Price ($/L) | PV (kW) | G1 | Gen (kW) | LI ASM | Natel49 (kW) | Converter (kW) | Dispatch | COE ($) | NPC ($) | Ren Frac (%) | Total Fuel (L) | Unmet load (%) | $CO_2$ (kg/yr) | Hours | Fuel (L) |
| 0.750 | | | 56.0 | 27 | 32.0 | 16.8 | LF | $0.0705 | $92,441 | 96.0 | 1,513 | 0 | 3,961 | 242 | 1,513 |
| 1.00 | | | 56.0 | 28 | 32.0 | 16.8 | LF | $0.0741 | $97,172 | 96.1 | 1,458 | 0 | 3,816 | 232 | 1,458 |
| 1.25 | | | 56.0 | 34 | 32.0 | 18.8 | LF | $0.0773 | $101,417 | 97.4 | 1,057 | 0 | 2,768 | 189 | 1,057 |
| 1.50 | 0.136 | | 56.0 | 37 | 32.0 | 21.8 | LF | $0.0799 | $104,743 | 97.9 | 835 | 0 | 2,187 | 150 | 835 |

**Table 4b** shows the corresponding overall outcome of the HRES simulation within the DFP range of 0.75 to 1.5 $ L$^{-1}$ for Scenario 2 in the ascending order of their cost effectiveness. Overall, the Hydro-PV-Diesel-Battery system remains cost effective for the entire DFP range of 0.75 to 1.5 $ L$^{-1}$. The cost of energy range is 0.0875 to 0.0997 $ L$^{-1}$ and the net present cost range is 179,741 to 204,816 $ L$^{-1}$.

**Table 4b. Output of Scenario 2 sensitivity analysis for Diesel Fuel Price range 0.75 to 1.5 $ L$^{-1}$.**

| Sensitivity | Architecture | | | | | | | Cost | | System | | | Gen | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Diesel Fuel Price ($/L) | PV (kW) | G1 | Gen (kW) | LI ASM | Natel49 (kW) | Converter (kW) | Dispatch | COE ($) | NPC ($) | Ren Frac (%) | Unmet load (%) | $CO_2$ (kg/yr) | Hours | Fuel (L) |
| 0.750 | 14.2 | | 77.0 | 64 | 32.0 | 29.5 | LF | $0.0875 | $179,741 | 95.5 | 0 | 6,713 | 298 | 2,564 |
| 1.00 | 13.7 | | 77.0 | 65 | 32.0 | 32.0 | LF | $0.0914 | $187,738 | 95.9 | 0 | 6,185 | 274 | 2,363 |
| 1.25 | 16.7 | | 77.0 | 69 | 32.0 | 31.7 | LF | $0.0966 | $198,435 | 96.5 | 0 | 5,625 | 288 | 2,149 |
| 1.50 | 20.7 | | 77.0 | 71 | 32.0 | 33.3 | LF | $0.0997 | $204,816 | 96.9 | 0 | 4,957 | 254 | 1,894 |

4.2.3 Comparison between scenarios

The outcomes for the plausible combination of renewable resources from HRES modelling in HOMER were assessed for their cost effectiveness and environmental performance to improve the reliability of the existing micro hydropower project at Khun Pang.

The aggregated cash flow for the different cost categories and the revenue generated from sale of electricity for all the scenarios are shown in **Figure 6**. These are based on a 25-year project life span, and use the assumptions on cost, energy tariff and time value for money representing market fluctuation for all the scenarios (see Section 3.6). First, the flows were calculated without including the environmental costs (left panel) and thereafter, all the costs were updated with corresponding lifespan environmental costs (climate and air quality costs) included (right panel). In all simulations, the added capacity to the Micro hydro were meant to fulfil the annual shortfall in electricity supply as: 4% (571 kWh) in Scenario 1 and 12.5% (3904kWh) in Scenario 2. It is noteworthy, the capital costs only account for the additional infrastructure for meeting the shortfall in the electricity supply for the two scenarios using the component configurations for the three cases (see assumptions in Section 3.6); the hydropower cost is not included in the cash flow because it is an existing component.

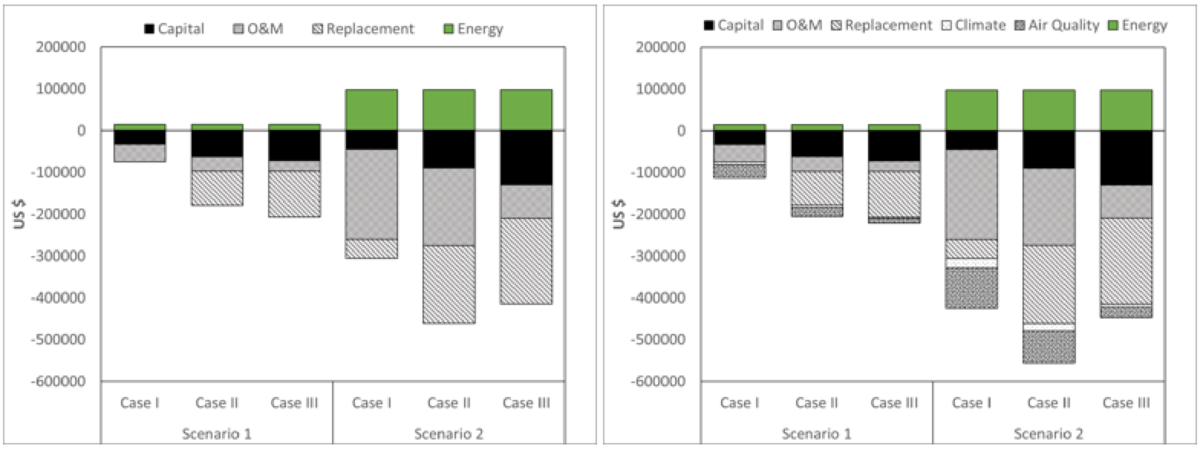


**Figure 6. Cash flow for the techno-economic-environmental analysis over the project lifespan.**

In terms of capital cost, Diesel Genset only (Case I) comes out as a clear winner for both the scenarios when environmental costs are note included, which is often expected. However, including additional storage using battery bank and converter (Case II) drastically increases the cost for Scenario 2 and seems to make it even more expensive than investing in renewable PV option (Case III).This is mainly attributed to higher O&M and replacement costs for components in Case II due to increased operating times in Scenario 2 (mainly Diesel Genset, battery banks and converters using assumptions from Table 1). On the other hand, when environmental costs were included, Cases II and III became comparable for Scenario 1 (lower shortfall), whereas Cases I and III became comparable for Scenario 2 (with three-fold increased shortfall). This shows the merit of including environmental costs in optimising the decision choice for making autonomous energy system using Micro hydro more sustainable.

Further, a comparison of the different hybrid configurations for the two scenarios was made on the basis of their economic and environmental performances, represented in terms of the Microhydro sustainability indicator values, to identify the most sustainable hybrid option (**Table 5**). All the scenarios have been compared with the baseline of the cheapest option i.e. Diesel Genset only, serving an unmet load of 4% (Scenario 1, Case I). While the Net present cost for Case III in both the scenarios are significantly high (respective increase of 179% and 458%), this is offset by the gains in their environmental costs (respective reduction of 62% and 13%). Therefore, the corresponding Microhydro sustainabiltiy indicator scores are favourable for Case III in both the scenarios. Using thie metrics, clearly the Diesel Genset only option is found to be the most unsustainable option.

**Table 5. Indicative estimates of the variation in the economic and environmental performance for the scenarios considered to meet the shortfall in electricity supply from the Khun Pang Micro hydro site (shown alongside are the corresponding % change to the baseline).**

| Scenario | Diesel Genset usage (hrs) # | Total O&M costs ($)# | Net present cost, NPC ($)# | Environmental cost, ENV ($)# | Total costs (NPC + ENV) # | Microhydro Sustainability Indicator (ENV/NPC) |
|---|---|---|---|---|---|---|
| **Scenario 1, Case I*** | 8,750 | 41,379 | 74,307 | 38,383 | 112,690 | 0.52 |
| **Scenario 1, Case II** | 6,050 (-31%) | 35,800 (-13%) | 178,312 (140%) | 26,539 (-31%) | 204,851 (82%) | 0.15 |
| **Scenario 1, Case III** | 3,750 (-57%) | 25,666 (-38%) | 207,195 (179%) | 14,646 (-62%) | 221,841 (97%) | 0.07 |
| **Scenario 2, Case I** | 27,344 (213%) | 214,787 (419%) | 305,339 (311%) | 119,946 (213%) | 425,285 (277%) | 0.39 |
| **Scenario 2, Case II** | 21,875 (150%) | 185,142 (347%) | 460,640 (520%) | 95,957 (150%) | 556,597 (394%) | 0.21 |
| **Scenario 2, Case III** | 6,350 (-27%) | 79,680 (93%) | 414,366 (458%) | 33,222 (-13%) | 447,587 (297%) | 0.08 |

*Baseline case for the Khun Pang Micro hydro site for meeting shortfall of 4% by Diesel Genset only.

# over 25 year project lifespan

## 5. Conclusions and Future work

The paper presents a mixed assessment framework for quantifying the tradeoffs between economic and environmental performances of an autonomous hybrid energy system using micro hydro, which extends the existing approach based on optimisiation of the net present cost. A micro hydro sustainability indicator is proposed to facilitate the descision making in selection of hybrid components while adding capacity to meet future shortfall in electricity supply from an existing Micro hydro more sustainably. The framework is implemented to a real case study site, utilising an existing micro hydro power plant for off-grid electricity generation within a national park in northern Thailand for two scenarios - Scenario 1 (circa 2016-17, annual shortfall of 4% i.e. 571 kWh) and Scenario 2 (circa 2025, projected future annual shortfall of 12.5% i.e. 3904 kWh). For each scenario, the following three cases with increasing complexity are evaluated: *Case I* – Economically preferred, i.e. cheapest initial cost (Microhydro with Diesel back up); *Case II* – Intermediate, i.e. low initial cost (Microhydro-Diesel backup-Battery storage); *Case III* – Environmentally preferred i.e. reduced Diesel Genset usage (includes Microhydro-PV- Diesel backup-Battery storage).

Our results show a clear merit in developing an integrated hybrid renewable energy system using micro hydro power in order to strengthen the off-grid energy infrastructure capacity, specifically applicable to ecologically sensitive locations in developing countries. This is reflected in more favourable scores of the micro hydro sustainability indicator for Case III from the analysis, compared to the cheapest Diesel only option (Case I) for both the scenarios. For Scenario 1, with lower shortfall in supply of 4% and lower Diesel fuel pricing (DFP: 0.75 $ $L^{-1}$), Case I came out as the clear winner, irrespective of whether the environmental costs were included in the assessment or not. For Scenario 2, with a three-fold increase in shortfall of 12.5% and the DFP stabilised around 1.25 $ $L^{-1}$, Case I remained the winner when the environmental costs were not included. However, with the environmental costs included, Case III turned out to be cost-competitive to Case I for meeting future electrical loads with improved reliability. It is noteworthy, the observed trends are based on assessment covering a project lifespan of 25 years; elongating the lifespan to 30 years or more is going to further strengthen the performance of Case III as the most preferred option, both ecnomically and environmentally.

The trade-offs scoped in this study were limited to the performance of a PV-Wind-Diesel-Battery HRES alongside an existing micro hydro plant for application in ecologically sensitive locations. Further consideration is needed to assess the environmental fate of other HRES configurations, with more efficient conversion technologies, such as bioenergy from combustion-based and anaerobic processes, geothermal, etc. Additional studies are also warranted to: a) assess the mitigation/retrofitting costs incurred in alleviating the environmental impacts; b) compare plausible scenarios for centralised vs. distributed microgeneration, such as setting up standalone PV system for meeting individual deferrable electrical loads alongside the Micro hydro serving the base load. Also, this study applied a constant micro hydro production capacity, assuming a steady stream flow rate. We recommend taking into account modelled climate change impact on stream flows to allow for any variation to the status quo performance of the micro hydro while making longer-term predictions.

## References


[1] Bódis K, Monforti F, Szabó S. Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data. Renew Sustain Energy Rev 2014;37:794–808. doi:10.1016/j.rser.2014.05.071.

[2] Nouni MR, Mullick SC, Kandpal TC. Providing electricity access to remote areas in India: Niche areas for decentralized electricity supply. Renew Energy 2009;34:430–4. doi:10.1016/J.RENENE.2008.05.006.

[3] Bracken L, Bulkeley H, policy CM-E, 2014 undefined. Micro-hydro power in the UK: The role of communities in an emerging energy resource. Elsevier n.d.

[4] IRENA. Hydropower Technology Brief. 2015.

[5] Budischak C, Sewell D, Thomson H, Mach L, Veron DE, Kempton W. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. J Power Sources 2013;225:60–74. doi:https://doi.org/10.1016/j.jpowsour.2012.09.054.

[6] Murni S, Whale J, Urmee T, Davis JK, Harries D. Learning from experience: A survey of existing micro-hydropower projects in Ba'Kelalan, Malaysia. Renew Energy 2013;60:88–97. doi:10.1016/J.RENENE.2013.04.009.

[7] Kenfack J, Neirac FP, Tatietse TT, Mayer D, Fogue M, Lejeune A. Microhydro-PV-hybrid system: Sizing a small hydro-PV-hybrid system for rural electrification in developing countries. Renew Energy 2009;34:2259–63. doi:10.1016/J.RENENE.2008.12.038.

[8] Palit D, Bandyopadhyay KR. Rural electricity access in South Asia: Is grid extension the remedy? A critical review. Renew Sustain Energy Rev 2016;60:1505–15. doi:10.1016/J.RSER.2016.03.034.

[9] Mandelli S, Barbieri J, Mereu R, Colombo E. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew Sustain Energy Rev 2016;58:1621–46. doi:10.1016/J.RSER.2015.12.338.

[10] Kruangpradit P, Tayati W. Hybrid renewable energy system development in Thailand. Renew Energy 1996;8:514–7. doi:10.1016/0960-1481(96)88910-5.

[11] OPEC. The Organization of the Petroleum Exporting Countries Annual Report 2015. 2016.

[12] Murni S, Whale J, Urmee T, Davis JK, Harries D. Learning from experience: A survey of existing micro-hydropower projects in Ba'Kelalan, Malaysia. Renew Energy 2013;60:88–97. doi:10.1016/J.RENENE.2013.04.009.

[13] Bhandari B, Lee K-T, Lee CS, Song C-K, Maskey RK, Ahn S-H. A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. Appl Energy 2014;133:236–42. doi:10.1016/J.APENERGY.2014.07.033.

[14] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 2014;32:192–205. doi:10.1016/J.RSER.2014.01.035.

[15] DEDE. The Micro Hydropower Project. Thai Ministry of Energy: 2017.

[16] Müller MF, Thompson SE, Kelly MN. Bridging the information gap: A webGIS tool for rural electrification in data-scarce regions. Appl Energy 2016;171:277–86. doi:10.1016/J.APENERGY.2016.03.052.

[17] Kumar S. Assessment of renewables for energy security and carbon mitigation in Southeast Asia: The case of Indonesia and Thailand. Appl Energy 2016;163:63–70. doi:10.1016/J.APENERGY.2015.11.019.

[18] Phuangpornpitak N, Kumar S. PV hybrid systems for rural electrification in Thailand. Renew Sustain Energy Rev 2007;11:1530–43. doi:10.1016/J.RSER.2005.11.008.

[19] Bekele G, Tadesse G. Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. Appl Energy 2012;97:5–15. doi:10.1016/j.apenergy.2011.11.059.

[20] Kougias I, Szabó S, Monforti-Ferrario F, Energy TH-R, 2016 U. A methodology for optimization of the complementarity between small-hydropower plants and solar PV systems. Renew Energy 2016;87:1023–30.

[21] Punys P, Dumbrauskas A, Kvaraciejus A, Vyciene G. Tools for Small Hydropower Plant Resource Planning and Development: A Review of Technology and Applications. Energies 2011;4:1258–77. doi:10.3390/en4091258.

[22] Catalão JPS, Pousinho HMI, Contreras J. Optimal hydro scheduling and offering strategies considering price uncertainty and risk management. Energy 2012;37:237–44. doi:10.1016/J.ENERGY.2011.11.041.

[23] Bortolini M, Gamberi M, Graziani A, Pilati F. Economic and environmental bi-objective design of an off-grid photovoltaic–battery–Diesel generator hybrid energy system. Energy Convers Manag 2015;106:1024–38. doi:10.1016/J.ENCONMAN.2015.10.051.

[24] Ogunjuyigbe ASO, Ayodele TR, Akinola OA. Optimal allocation and sizing of PV/Wind/Split-Diesel/Battery hybrid energy system for minimizing life cycle cost, carbon emission and dump energy of remote residential building. Appl Energy 2016;171:153–71. doi:10.1016/J.APENERGY.2016.03.051.

[25] Roth IF, Ambs LL. Incorporating externalities into a full cost approach to electric power generation life-cycle costing. Energy 2004;29:2125–44. doi:10.1016/J.ENERGY.2004.03.016.

[26] ExternE. External Costs of Energy 2017. http://www.externe.info/ (accessed March 20, 2017).

[27] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. doi:10.1016/j.apenergy.2009.09.026.

[28] Zweibel K, Mason J, Fthenakis V. A Solar Grand Plan. Sci Am 2008;298:64–73. doi:10.1038/scientificamerican0108-64.

[29] Darling SB, You F, Veselka T, Velosa A. Assumptions and the levelized cost of energy for photovoltaics. Energy Environ Sci 2011;4:3133. doi:10.1039/c0ee00698j.

[30] HOMER. Hybrid Optimization of Multiple Energy Resources (HOMER®) Pro Version 3.9 Program 2017.

[31] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88:502–7. doi:10.1016/j.apenergy.2010.03.006.

[32] Mathiesen BV, Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. Appl Energy 2011;88:488–501. doi:10.1016/J.APENERGY.2010.03.001.

[33] Manfren M, Caputo P, Costa G. Paradigm shift in urban energy systems through distributed generation: Methods and models. Appl Energy 2011;88:1032–48. doi:10.1016/J.APENERGY.2010.10.018.

[34] Banar M, Özdemir A. An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods. Transp Res Part D Transp Environ 2015;41:88–105. doi:10.1016/J.TRD.2015.09.017.

[35] Özkan A, Günkaya Z, Tok G, Karacasulu L, Sustainability MM-, 2016 undefined. Life cycle assessment and life cycle cost analysis of magnesia spinel brick production. Mdpi.com n.d.

[36] BEIS. Carbon valuation - GOV.UK. Dep Business, Energy Ind Strateg 2018. https://www.gov.uk/government/collections/carbon-valuation--2 (accessed April 25, 2018).

[37] De Nocker L, Spirinckx C, Torfs R. No Title. 2nd Int. Conf. LCA Agric. Agro-industry For. Brussels, 3-4 December 1998, 1998, p. 1–10.

[38] DEDE. Khun Pang Hydropower Project. Thai Ministry of Energy: 2017.

[39] Pudpong N, Hajat S. High temperature effects on out-patient visits and hospital admissions in Chiang Mai, Thailand. Sci Total Environ 2011;409:5260–7. doi:10.1016/J.SCITOTENV.2011.09.005.

[40] Grabowsky V. Regions and national integration in Thailand, 1892-1992. Otto Harrassowitz Verlag; 1995.

[41] Jones R V., Lomas KJ. Determinants of high electrical energy demand in UK homes: Appliance ownership and use. Energy Build 2016;117:71–82. doi:10.1016/J.ENBUILD.2016.02.020.

[42] Dawson C. Introduction to research methods: A practical guide for anyone undertaking a research project. Hachette UK; 2009.

[43] Thomas G. How to do your research project: A guide for students in education and applied social sciences. Sage Publications; 2013.

[44] Surrimachine. Tea Cutting Machine 2017. http://www.surrimachine.com/ (accessed July 20, 2017).

[45] WMO. Manual on low-flow estimation and prediction. Operational Hydrology Report No. 50, WMO-NO. 1029. 2008.

[46] DEDE. Solar Potential in Thailand 2017. http://weben.dede.go.th/webmax/content/wind-power-and-its-potential-thailand (accessed August 10, 2017).

[47] PTT. Oil Price in Chaing Mai. 2017.

[48] ShellThailand. Oil Price in Thailand. 2017.

[49] Madriz-Vargas R. Design and Simulation of a Renewable Energy Hybrid System Solution for the Rural House in Costa Rica. 2013.

[50] Khan MJ, Iqbal MT. Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. Renew Energy 2005;30:835–54. doi:10.1016/J.RENENE.2004.09.001.

## Appendix A: HRES modelling principles

| Eqn. # | Formulation | Description |
|---|---|---|
| **I. Electrical power modelling** | | |
| A.1 | PV power output (Watts): $P_{PV} = G_T * A_{PV} * \eta_{PV}$ | $G_T$ : solar irradiance profile ($Wm^{-2}$)<br>$A_{PV}$ : PV panel area ($m^2$)<br>$\eta_{PV}$ : conversion efficiency of the PV panel (typically ranging between 15-20%, depending on the normal operating cell temperature) |
| A.2 | Micro hydropower output (Watts): $P = \eta \rho g Q H$ | $\rho$ : water density (kg $m^{-3}$)<br>$g$ : acceleration due to gravity (9.81 m $s^{-2}$)<br>$Q$ : water flow rate through the turbine ($m^3 s^{-1}$)<br>$H$ : effective water head (m)<br>$\eta$ : efficiency of hydro power systems (typically, $\eta = \eta_{turb} * \eta_G$, where $\eta_{turb}$ is turbine efficiency; $\eta_G$ is generator efficiency |
| A.3 | Efficiency of water storage pump: $\eta_p = (2.725\ Q * H) / P_{mech}$ | $Q$ : water flow rate through the turbine ($m^3 s^{-1}$)<br>$H$ : effective water head of pump( m)<br>$P_{mech}$ : mechanical power of water pump (Watts) |
| **II. Cost modelling** | | |
| A.4 | Total lifespan cost (TLSC, includes capital cost, operation and maintenance cost that combine fixed and variable part and replacement cost over the lifespan of the system): $TLSC = \sum_{j=0}^{N_s} \frac{C_j}{(1+d)^j}$ | $N_s$ : the lifespan of the system<br>$C_j$ : the present value of TLSC<br>$d$ : the annual discount rate<br>$j$ : iteration 0,1,2,…,$N_s$ |
| A.5 | Capital cost, it is the initial cost of all components of the HRES and is computed for year j=0. The capital cost of each component is a unit cost of the product. The overall capital cost of the HRES is given by: $C_c = \sum_{cop} C_{u,comp} S_{comp} (1 + \alpha_{ins,comp})$ | $C_{u,\ comp}$ : unit cost of each component<br>$S_{comp}$: size of individual HRES component<br>$\alpha_{ins,comp}$ : installation cost of the individual HRES component |
| A.6 | Operation and maintenance costs (O&M costs, comprises of two parts - variable and fixed. These are costs included from taxes, insurance, repair parts cost and land and substation rentals): $C_{O\&M,\ F+V} = \sum_{comp} C_{O\&M,F,comp} + \sum_{comp} C_{O\&M,Vcomp}$<br><br>Where, $C_{O\&M,F,comp} = \alpha_{O\&M,comp} * C_{c,comp}$<br><br>O&M annual variable part cost of a Diesel generator is given by: | $C_{O\&M,F}$: Fixed operation and maintenance cost component<br>$C_{O\&M,V}$ : Variable operation and maintenance cost<br><br>$C_{c,comp}$ : capital cost of all components<br>$\alpha_{o\&M,comp}$ : operation and maintenance cost of the individual HRES component<br><br>$P_{h,D}$ : hourly averaged Diesel power<br>$P_{D,nom}$: nominal Diesel power<br>$T_D$: total number of hour of Diesel generator operation<br>$C_{fuel}$: fuel price (typically DFP, US\$ $litre^{-1}$) |

| | | |
|---|---|---|
| | $C_{O\&M,V,D} = \frac{0.246\sum_{i=1}^{8760}\overline{P}_{h,D_i} + 0.08145P_{D,nom}T_D}{1000}C_{fuel}$ | |
| A.7 | Replacement cost, includes cost for each component that will demand to be installed more than once during the life cycle of the system. The PV array do not need to be replaced as their lifetimes are usually matched to the lifespan of the system. However, the battery needs to be replaced because its lifetime depends on the charge-discharge regimes. The replacement cost is calculated as a function of the capital cost as follows:<br><br>$C_r = \sum_{comp} n_{r,comp}\, C_{c,comp}$<br><br>$n_r$ for batteries:<br><br>$n_{r,B} = \left[ \max\left\{ \frac{N_S}{N_{nomB}}, \frac{N_S}{N_{eq,B}} \right\} \right]$ | $n_r$ : number of replacements during the lifespan of the system<br>$C_c$ : capital cost of components.<br><br>$N_{nom,B}$ : nominal life of battery<br>$N_{eq,B}$ : equivalent life of battery |
| A.8 | Levelised cost of energy (*LCOE*, determined as the ratio of the total annualised cost of the system and the annual energy output of the system) as follows:<br><br>*LCOE = (TLSC * UCRF)/* $P_t$<br><br>*UCRF* is the uniform capital recovery factor, which depends on the discount rate as follows:<br><br>$UCRF = \frac{d(1+d)^{N_s}}{(1+d)^{N_s} - 1}$ | $P_t$ : annual energy output<br><br>$N_s$ : life span of the system (year)<br>$d$ : annual discount rate (%) |

**Appendix B: Survey questionnaire form**

1. What type of dwelling do you live in?

- Cabin
- Single house (1 level)
- Single house (2 level)
- Other (specify)

2. How many rooms does your dwelling have?

- It's a studio.
- One.
- Two.
- Three.
- Four.
- Five or more

3. How many members are in your household?

Male |__|__| Female |__|__| Children |__|__|

4. What time do you use electricity during a day?

|__| 6.00 - 8.00 |__| 10.00 - 12.00 |__| 14.00 - 16.00

|__| 18.00 - 20.00 |__| 22.00 - 24.00

5. What kind of light bulbs do you have in your dwelling?

- "Traditional" Incandescent Bulbs - size……………Watts, quantity………..unit
- Compact Fluorescent Lamps. - size……………Watts, quantity………..unit
- Fluorescent Lamps. - size……………Watts, quantity………..unit
- Halogen Lamps. - size……………Watts, quantity………..unit
- Other ……………………………………………………………………………………

6. How many hour per day of those incandescent bulbs are turned on?

|__|__|

7. Which electrical appliances do you have in your dwelling?

- Refrigerator - size……………. Litre, quantity………….. ..unit
- Table Fan - size……………. inches, quantity………….. ..unit
- Iron - size……………. Watts, quantity………….. ..unit
- Electric Rice Cooker - size……………. Litre, quantity………….. ..unit
- Television - size……………. inches, quantity………….. ..unit
- Mobile Phone - size……………. inches, quantity………….. ..unit
- Other……………………………………………………………………………….

8. How many hours per day was used electrical appliances?

For comfort (table fan, iron) |__|__|

For cooking (electric rice cooker) |__|__|

For entertainment (TV, mobile phone) |__|__|

9. Which electrical appliances do you want to add in your dwelling?

- Air Conditioner - size……………. BTU, quantity………….. ..unit
- Washing Machine - size……………. Kg, quantity………….. ..unit
- Water Heater - size……………. Watts, quantity………….. ..unit
- Electric Pan - size……………. inches, quantity………….. ..unit
- Electric Kettle - size……………. Litre, quantity………….. ..unit
- Refrigerator - size……………. Litre, quantity………….. ..unit
- Table Fan - size……………. inches, quantity………….. ..unit
- Iron - size……………. Watts, quantity………….. ..unit
- Electric Rice Cooker - size……………. Litre, quantity………….. ..unit
- Television - size……………. inches, quantity………….. ..unit
- Mobile Phone - size……………. inches, quantity………….. ..unit
- Other……………………………………………………………………………….